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Ultrasonic imaging techniques for non-destructive testing of nuclear reactors, cooled by liquid metals: review

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Abstract:
In some nuclear reactors the core is cooled by means of liquid metal alloy, for example, lead-bismuth eutectic alloy. For safety and licensing reasons, an imaging method for evaluation of status of the interior of reactor has thus to be developed. There are no any other physical means except ultrasonic, which would enable to inspect inner reactor parts submerged in the opaque hot liquid metal. The operating conditions significantly restrict the possible architecture of the visualization system and materials, which can be used On the other hand, the system should be 'simple' enough to enable implementation of it in above mentioned conditions. The paper is devoted to review of ultrasonic imaging techniques, suitable for use in the opaque hot liquid metal alloy. Also several modeling approaches, which could be used for acoustic modeling of the reactors, are reviewed here also.
Keywords: ultrasonic imaging, nuclear reactors, high temperature, opaque, liquid metal.

Introduction

In some nuclear reactors, for example, accelerator driven sub-critical fission reactor systems, the core is cooled using heavy liquid metal. One of such systems is the accelerator driven system MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), which is cooled by means of lead bismuth eutectic. The use of heavy liquid metal for reactor devices possesses problems with the required inspection and maintenance due to the opaque nature of the medium [1, 2]. In contrast to water-cooled reactors, it is not possible to inspect optically inner reactor parts, submerged in the hot liquid metal. In order to solve the inspection issue of the reactors, cooled with liquid metal, the Belgian Nuclear Research Centre SCK•CEN and the Ultrasound Institute in Kaunas University of Technology, Lithuania are collaborating on the development of ultrasonic imaging technique for this particular application [3 - 8].

The ultrasonic imaging system, which is in a development stage now, must operate in very harsh conditions including high temperature (160^o – 450 °C), chemical activity of liquid metal and strong gamma radiation (up to 30 kGy/h). These conditions significantly restrict the possible structure of the visualization system.

In this paper different ultrasonic imaging systems, used for nondestructive testing of the nuclear reactors, especially in similar fast breeder reactors, cooled by liquid sodium, are reviewed. Also imaging systems, used for underwater imaging are described, because some ideas from underwater imaging in turbid water can be adapted for imaging of nuclear reactors, cooled by liquid metals. One of the ways to find the best architecture of ultrasonic visualization system is to develop acoustic computer model, which enables to simulate propagation of ultrasound in a any media and to calculate the signals reflected by the complicated components of reactor interior. Therefore several modeling approaches, which could be used for acoustic modeling of the nuclear reactors, are reviewed here also.

Ultrasonic viewers in liquid sodium reactors

Liquid sodium is used as a coolant in the fast breeder reactors. Liquid sodium is also opaque (like lead bismuth) to ordinary light, therefore, for viewing inside liquid sodium reactors ultrasonic techniques are used. At normal online conditions the sodium temperature can be about 600 °C [9]. However, at a routine maintenance shutdown sodium temperature is lowered to 250 °C [9], and most experiments were performed at this lower temperature [9 - 12]. At cold shutdown temperature is lowered even to 150 – 180 °C and some inspections were performed at this temperature [13, 14].

In general, frequencies between 1 MHz and 5 MHz are used for imaging of under-sodium reactors [9]. Most often devices are used to monitor the refueling process. During refueling it is essential to ensure that the region between the core top and the above core structure is not obstructed [9].

For visualization of the reactor interior different system configurations are used. It seems that there is no one best configuration for this special case.

Karasawa *et al* use 5 MHz matrix arrayed transducer, in which are 36 x 36 (1296) elements (one element is 2,5 mm x 2,5 mm PZT) arranged with the 5 mm interval and sealed by a thin metal diaphragm [11]. The reference target images were synthesized at 0,4, 0,7 and 1.0 m distances from the transducer at the 200 ±10 °C temperature. To synthesize the 3D images the cross-correlation technique and afterwards SAFT was applied [11].

In the French fast reactor Phenix a high frequency sonar device, consisting of two transducers, is used. One is used as a transmitter, the another – as a receiver. Ultrasound is conveyed to the core top via liquid-filled waveguides, with mirrors at the bottom of the waveguides to direct and receive signals from over the core. The core top region can be examined by mechanically rotating the system [9]. On Phenix two types of ultrasonic examinations were performed [13, 14]: ultrasonic examination of the reactor vessel upper hangers and ultrasonic examination of the core support conical shell. For inspection of the welds in the hangers the special 8 mm thick transducer with a built-in feeding device for the coupling fluid was developed, which can withstand temperatures between 110 and 130 °C [14]. For inspection of the welds in the conical shell ultrasonic signals were transmitted at different frequencies depending on the weld of interest from the outer surface of the main vessel. The signal acquisition system was redesigned to accept long delays of the signals traveling from the far side of the structure. The developed system detects 100 mm long defects [14].

At Hanford, USA, the imaging system consists of a horizontal mechanical arm carrying a number of downward-viewing transducers. The arm is scanning over the top of the core in a series of arcs. In order to extend coverage at the end of each arc the arm is extended radially [9].

The ultrasonic rigid under sodium viewer was used in an operational British fast reactor. Its main purpose was to assist in the assessment of a core component distortion. The system consists of an 11 m long tube 25 cm in the diameter with 12 pulse-echo transducers. Eight of them point downwards and four sideways. Only four of the downward looking transducers are used at one time. The transducers are located 200 mm from the core. They were scanned over the core using the combination of rotating shield movements and rotation about its own vertical axis [9].

Swaminathan *et al* [12] from India developed the ultrasonic under-sodium viewing system in Fast Breeder Test Reactor. The system was used as a sweep-arm to scan the space below the core cover plate mechanism (CCPM) of the reactor to find any obstacle and also to image CCPM. The viewer is 6 m long and 90 mm in the diameter. It uses the ultrasonic transducer mounted horizontally at its bottom end, which is rotated [12].

Imbert *et al* [15] are taking into account information not only from specular echoes, but also from backscattering due to rough metallic surfaces as well the echoes diffracted by the edges. The imaging system is based on an orthogonal imaging concept, and is comprised of two linear arrays each of 128 elements laid out orthogonally and operating at the centre frequency of 1.6 MHz. The orthogonal imaging concept is based on conical holography. This concept was used in several underwater acoustic systems. One array placed vertically is used to transmit a fan shaped beam deflected along a given elevation angle and focused at a given distance. The second array, placed horizontally, is used to receive an identical beam deflected by a given azimuth and focused at several distances or focal zones [15].

A phased array ultrasonic inspection system PAULI [16], which is modified medical ultrasound imaging system, allows to obtain electronically scanned ultrasonic images of the inside of nuclear power plant components. This system has a phased array consisting of 64 or 128 transducers with the 7.5 MHz frequency. The PAULI system can provide ultrasonic images in a real time [16].

Visualization underwater

The imaging using ultrasonic waves is often used under conditions, where imaging by other means (light waves, radio waves) is difficult to apply. Underwater imaging in turbid water [17] or imaging of the seafloor beneath the mud [18] are some of the cases, where ultrasonic imaging is extensively used. Some ideas from underwater imaging systems could be used for imaging of nuclear reactors, cooled by liquid metals, because in underwater ultrasonic imaging systems signals are transmitted and received from 1 meter or more.

One of ultrasonic underwater imaging systems to view objects in turbid water uses the 600 kHz transducer and acoustic holography to get real time 3D images [17]. The 3D image is reconstructed by means of a single transmitting and receiving process. For transmitting one transducer, 15 mm in diameter is used. For receiving 114 transducer array, each transducer 7 mm in diameter is used. The transmitter is located at the center, and receivers are arranged alternately at spacing 10λ (Fig.1). The information about the phase and amplitude is recorded. Ultrasonic wave is transmitted only once [17].

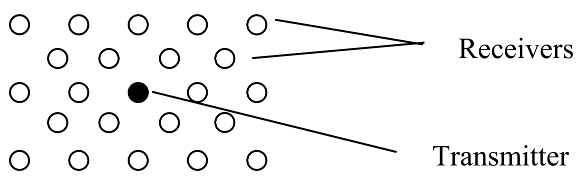

Fig.1. **Possible arrangement of transducers**

Narrow-beam sub bottom profiler for archaeological applications uses commercially available side-scan sonar with rectangular transducers laid out in rows to approximate a circle (the array size – 30 cm). The frequency is 150 kHz, and the ultrasonic beam is narrow (~2 degrees) [18].

A realistic image of the inspected structure is not always needed. Sometimes it is enough to distinguish between planes, edges and corners. Various sonar arrays were proposed for classifying planes, corners and edges. It was established that two transmitters and two receivers are sufficient to distinguish planes, corners and edges [19, 20]. The receivers are closely spaced so as to minimize the correspondence problem of associating different receiver echoes from multiple targets [20].

Phased arrays, sparse arrays or single transducers?

A 3D scan of the object can be obtained either using mechanical scanning of a focused transducer or by electronically steering an ultrasound beam. The use of 2D phased-array transducers allows steering of the ultrasonic beam in all directions, but unacceptably large amount of transducer channels must be used [21]. In ultrasonic testing, a sparse array can increase the resolution by enlarging the aperture without increasing system complexity [22], or reduce the number of elements without reducing the aperture and maintaining the image quality [23]. The term *sparse array* refers to an array, where some of the elements have been removed from the full array, so that array no longer satisfies the spatial sampling criterion [23]. In traditional phased arrays the placement of the array elements must satisfy the spatial sampling criterion – interelement distance has to be between half and one wavelength of the pulse center frequency [23]. In order to decrease the number of channels, sparse arrays with different aperture apodization functions in transmitting and receiving apertures are proposed [21].

In terms of image quality one of the most important features of an array's point spread function are its side lobes and grating lobes [23]. Side lobes are present in the radiation pattern due to a finite size of the transducers. The grating lobes are peaks in the point spread function at other angles than the main lobe, caused by violation of the spatial sampling criterion [23]. The grating lobes appear due to periodic nature of the linear arrays. They are outside the scanned region if the spacing between elements is $\lambda/2$, but inside the field if the spacing increases. To obtain a high resolution with a small number of channels, arrays with the spacing $>\lambda/2$ have to be used [21]. Randomly sparsed arrays do not have a periodical sampling pattern and therefore they do not have prominent grating lobes in the radiation pattern. However, side-lobe energy at the level of ~ -30 dB from the peak value is present. Therefore the ultrasound system must be optimized in terms of the two-way (transmit and receive) directivity pattern. The approach is based on the use of an effective aperture, also known as a co-array [21]. The design of the transmitting and receiving aperture is reduced to the problem of finding a suitable effective aperture with the desired Fourier transform. The elements in the effective aperture should be spaced at $\lambda/2$, and the weighting function should not have discontinuities to avoid side and grating lobes [21]. Also the periodic Vernier arrays are proposed, while they have lower side lobe energy than the sparse arrays, and they have the potential of giving images with a higher contrast [21].

In a synthetic transmit aperture imaging one element transmits a pulse and all elements receive the echoes. Then the next element is excited and this is repeated until the whole transmit aperture is synthesized. The final synthetic image is a coherent sum of all beam-formed images. In this way, the final image is fully focused both in transmitting and receiving modes [24]. 64 element array with $\lambda/2$ element spacing has been used for simulations. Four elements (1, 22, 43, 64) were used in a transmitting mode and the entire array was used for receiving [24].

Enlarging the array aperture is an effective method to improve a resolution, but if the array aperture is enlarged only by adding independent channels then the systems complexity increases. Application of sparse arrays is an effective method to improve resolution. A periodic sparse array is a very easy method, but it does not have the best performance. A method based on the Minimum Redundancy Linear Array was proposed by P. Yang [22]. A sparse array with independent 16 active elements and an aperture of 36 element width is used [22].

The image quality of a volumetric imaging system can be improved also by curving phase-steered sparse periodic two-dimensional arrays in one direction [23]. It was shown [23] that curving is equivalent to removing some of element periodicity, that means adding "randomness" to the layout. Curving allows suppressing the grating lobes located at directions along the curvature [23].

Ultrasound image quality can be improved also by using 1.75D arrays – by incorporating elevation information. The results obtained using the 6.7 MHz 1.75D 8x128 array (1024 elements) are described [25].

Improvement in the image quality also can be achieved using the phased array in combination with the inverse wave field extrapolation [26]. This real time imaging technique takes into account all possible reflections, diffraction's and wave mode conversions. A data set is created by firing one single element in the phased array and receiving the response on all the available elements [26].

Due to harsh operation conditions the systems structure should be as simple as possible, but should provide a good resolution. Phased arrays give a very good resolution, but are very expensive and too complicated to implement in harsh conditions. On the other hand, one or two transducers would require long scanning time for imaging of the big structures and would have not enough imaging possibilities, as well not good enough resolution. Therefore, the best solution would be to use sparse arrays - their structure could be not too complicated, but they can have the aperture big enough to have a reasonable resolution.

Modeling

Harsh conditions significantly restrict the possible architecture of the visualization system - the system should be 'simple' enough to enable implementation of it in above mentioned conditions. One of the ways to solve this task is to develop acoustic computer model, which enables to simulate propagation of ultrasound in a liquid metal and to calculate the signals reflected by the complicated components of reactor interior. Therefore several modeling approaches, which could be used for acoustic modeling of the reactors, are reviewed here also. Several modeling approaches for approximation of objects through the series of facets (rectangular, triangular) are available [27-29].

The shape could be described by subdividing the target into a large number of rectangular facets [27]. The facets are described by center of the facet, the outward normal to the facet, the area of the facet and the length vectors of the two sides of the facet. Scattering from all illuminated facet are summed coherently to get the net scattered pressure. Shadowing by the target is calculated solving a set of quadratic equations for each surface in term of the arc length of the eigen-ray to determine the point of intersection of the eigen-ray with the surface [27].

Complex 3D objects could be represented by densely packed surfaces of facets that are small compared to the wavelength [28]. The coordinate and the surface normal of the facets are computed and stored. To model 3D objects basic shapes like the sphere, cylinder and cone are superimposed. Basic building block of these shapes is the circle. The object surface is constructed by stacking circles with appropriate radius one behind other. Removal of overlapping surfaces is achieved by a modified ray-tracing algorithm, which removes all those coordinates which fall in the shadow volume behind the visible surfaces. The insonified facets are computed by selecting facets whose surface normal have a positive component towards the sonar view point. It is assumed that the energy propagates along straight ray paths [28].

The surface of the complex 3D object also can be represented by plane triangular facets [29]. The plane triangular facet is suited for approximation of all types of surfaces because of its co-planar property. Each facet in the three-dimensional space is represented by its vertex points and the unit surface normal vector pointing out of the body [29].

Conclusions

The analysis of different imaging techniques used in nuclear reactors and for underwater imaging had shown that there is no optimal technique available. Different authors use very different imaging system structures with a different number of transducers. Taking into account harsh conditions, in which system has to operate, it is better to keep the system configuration as simple as possible. Therefore, in order not to lose a resolution, the best solution would be application of sparse arrays.

For acoustic modeling of a nuclear reactor the possible solution could be representation of the surfaces by triangular facets, which are represented in 3D space by three vertex points and the normal vector.

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E. Jasiūnienė

Ultragarsinių vizualizacinių sistemų, skirtų atominių reaktorių, aušinamų skystu metalu, neardomajai kontrolei, apžvalga

Reziumė

Kai kuriuose atominiuose reaktoriuose aušinimui naudojamas ne vanduo, o skystas metalas, pavyzdžiui, švino ir bismuto lydinys. Saugumo sumetimais turi būti sukurta tokio tipo reaktorių vidaus vizualizavimo sistema. Vienintelis įmanomas būdas vizualizuoti vidines reaktoriaus dalis karštame ir neskaidriame skystame metale - panaudoti ultragarso bangas. Sudėtingos darbo sąlygos labai apriboja galimą ultragarsinės vizualizacinės sistemos architektūrą ir medžiagas, kurios gali būti panaudotos. Kita vertus, ultragarsinė vizualizacinė sistema turėtų būti gana paprasta, kad ja galima būtų naudotis tokiomis sudėtingomis sąlygomis. Šiame straipsnyje pateikiama tinkamų ekstremaliomis sąlygomis ultragarsinių vizualizacinių metodų, taip pat ultragarsinių signalų sklidimo atominiuose reaktoriuose modeliavimo metodų apžvalga.

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